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virtual space depicted in pictorial displays. Recent experiments are summarized which define the conditions under which geometric distortions affect perceived space. Under some conditions, an active perceptual compensation process exists which discounts the compression and expansion of virtual space. In addition, regularity or familiarity of the viewed object greatly reduce the sensitivity to distortion of spatial information.

EFFECTS OF PROJECTIVE DISTORTION ON PERCEPTION OF GRAPHIC DISPLAYS

Richard R. Rosinski

University of Pittsburgh

ABSTRACT

Graphic displays can provide accurate representations of three-dimensional space only if they are viewed from the geometric center of projection. Other viewing conditions result in distortions of virtual space. A current paradox of graphic display perception is that such distortions are not always evident in perception of depicted space.

This paper presents an analysis of the geometric basis for distortions of the virtual space depicted in pictorial displays. Recent experiments are summarized which define the conditions under which geometric distortions affect perceived space. Under some conditions, an active perceptual compensation process exists which discounts the compression and expansion of virtual space. In addition, regularity or familiarity of the viewed object greatly reduce the sensitivity to distortion of spatial information.

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EFFECTS OF PROJECTIVE DISTORTION ON PERCEPTION OF GRAPHIC DISPLAYS

Richard R. Rosinski

University of Pittsburgh

Introduction

The work that I will discuss today is directed toward a fundamental issue in the study of Visual Perception, and in the application of perceptual studies to the design of graphic displays. Specifically, what is the relationship between visual stimulation or visual information, on the one hand, and perceptual experience on the other. This is a fundamental question, that one would have hoped could have been settled long ago, but this is not the case. In the area of space perception, for example, there is little agreement regarding the extent to which the characteristics of the visual array projected to the eye determine the nature of perceived experience.

When one considers the perception of space represented in pictures, these issues are relevant to both a theoretical psychological and an applied engineering perspective. From the standpoint of perceptual theory, the basic nature of picture perception has been ambiguous. Originally, Gibson (1951) and many of his colleagues interpreted the phenomena of picture perception as evidence for a direct theory of perception. Individuals were able to make accurate judgments of depth represented in pictures; and there was a suggestion that under the right conditions, observers were unaware that they had been viewing pictures. The interpretation for such results was that the array projected to the eye from the picture was identical to the array from the real world. Geometrically, the information was the same in the two cases. Therefore, the same processes which were involved in the pick-up of information from the real world could be used to pick up the information projected from a photograph. Pictures acted as informational surrogates for actual spatial layouts. Considerable evidence was accumulated regarding the equivalence of pictures and real scenes, and this surrogate theory of picture perception was perhaps the most influential over the last two decades.

There are substantial problems with such a view that are fairly easy to point out. There is a geometric isomorphism between the pictorial and environmental arrays only when a picture is viewed from the geometrically correct center of projection. When a picture is viewed from some other place, the geometric relations are changed; the space specified by the picture is distorted in the sense that it does not correspond to the actual scene that was depicted. Now, if space perception in pictures were simply and directly based on the information projected to the eye, such distortions should be evident in perceived space. Our impressions and judgments of space should be similarly distorted. But this does not occur. Pictured space does not seem to distort when we walk past a picture; we are usually unaware of the distortions present in studio photography; and artists and photographers have long known that it is often necessary to distort perspective to make a scene "look right".

In response to such difficulties with the surrogate theory, Gibson (1979) later argued that picture perception was very different from normal space perception in that it was indirect and mediated by some interpretive mechanism. Hagen (1974) proposed that picture perception involved an entirely different "mode" of perception, although the nature of this mode was not specified. Others such as Pirenne (1970) suggested that there was a compensation process which, in some way, was able to discount the effects of geometric distortions on perception.

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2. Current Address: Bell Laboratories; Lincroft, N. J. 07738.

From an applied perspective, the role of non-visual processes in the perception of space can play an important role in graphics design. There has been increased use of two-dimensional displays of three-dimensional space in such areas as simulation, master-slave robotics, remote piloting of vehicles, and in multi-variable integrated displays. In each of these applications it is necessary that an operator respond to perceived space from a two dimensional display. Geometric accuracy (although not necessarily realism) has been an important aspect of display design. The non-visual factors that affect the way that spatial information is used would be important variables in design of spatial displays.

The general questions that have been at the focus of the research that I will discuss concern the determination of spatial perception by the geometry of the visual array, and the nature of non-visual compensation processes that affect perception of space based on graphic displays. That is, processes which can discount the effects of projective distortions of the visual array. I will simply assert here that there is no optical information available from a picture or graphic display for the presence, absence, or extent of any projective distortion. Ideally, a compensation phenomena, were it to exist, would operate primarily when distortions existed; but if no optical information for distortion is present, how is the presence of a distortion detected?

Early evidence for a spatial compensation process is rather sparse, and many including myself doubted its existence. One investigator (Perkins, 1973) showed that shape distortions were not perceived until the projective distortion was quite extreme; yet these data might not indicate a perceptual compensation as much as a failure of discrimination of shape categories. A second investigator (Hagan, 1974) found no perceptual effect of distortions on relative depth, but information for relative depth is not affected by such distortions. Occasionally the magnitude of the geometric distortion has been miscalculated, so conclusions about compensation were moot. Finally, many arguments, and the data used to support them have been intuitive and phenomenological. One's intuition or awareness is not relevant here since the empirical question is whether perception is in greater correspondence with the distorted projection or with the environment that the picture is supposed to represent.

Preliminary studies that were conducted in my lab (Rosinski, Mulholland, Degelman, & Farber, 1980), however, provided evidence for some form of pictorial compensation. In a task requiring judgments of surface orientation represented in pictures, one arrangement showed a close correspondence between perceived slant and the distorted projection, a second showed no effects at all of the projective distortion. This particular pattern of results could only be reconciled in terms of some compensation mechanism.

An initial issue was to assess the degree to which perceived space corresponded to distorted space. To accomplish this, Farber and I (Farber and Rosinski, 1978; Rosinski and Farber, 1980) developed a geometrical analysis that could be used to quantitatively determine the effects of projective distortions on depicted space. We reanalyzed a number of early studies to determine the extent of the effects of distortion. Based on these findings, a research program was initiated under the sponsorship of the Office of Naval Research to specifically test the correspondence between perceived and geometrically specified space.

The essential nature of this analysis can be seen in Figure 1. This drawing represents a square-tiled surface lying at an angle on another square-tiled surface. The same perspectival rules used to create such a drawing can be used to analyze distortion. For either a real scene viewed directly, or for a picture viewed from the geometrically correct center of projection a number of geometric relations obtain. For any surface, a line from the eye to the primary vanishing point has the same orientation as the slant of the surface. The angle between the lines from the eye to the primary vanishing point of one surface, and the line from the eye to the primary vanishing point of the second surface corresponds to the angle between the two surfaces. The angle between the eye and the two vanishing points for the tiles diagonals should be 90 degrees.

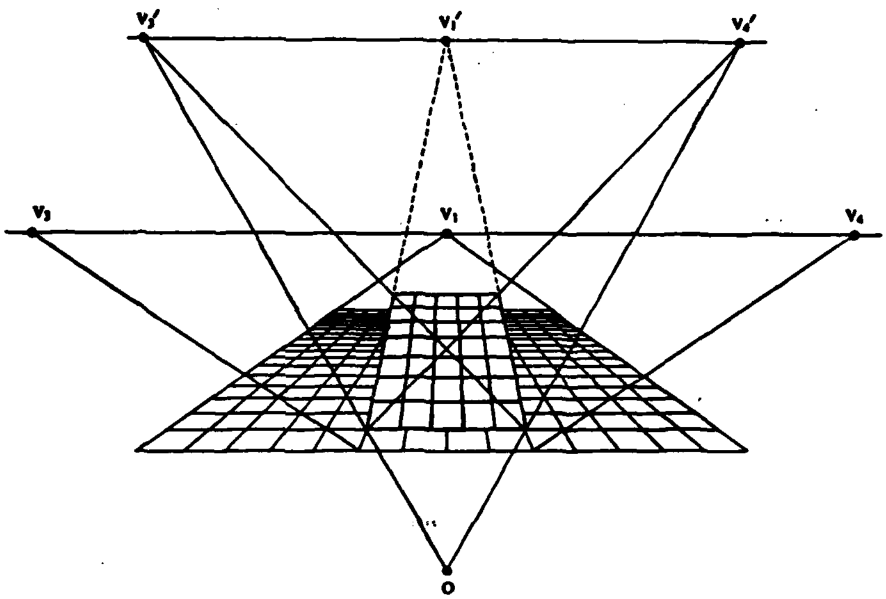

Figure 1. Geometry of Surface Layout.

It follows from this sort of analysis that if the eye is positioned at the correct center of projection, the visual array from the display specifies the location of objects and surfaces in the world. That is, when the eye is at the center of projection, the environmental and pictorial arrays are identical, and the displayed space corresponds to the real scene. This is the simple geometry that is the basis for linear perspective in drawings and in computer graphic representations of three-dimensional space.

How can we characterize the distortions of space that result when the viewing point is changed? We adopt a simple convention. For any new viewing point, we could describe the new virtual space which would have generated the new array. A comparison of the new virtual space with the the original virtual space gives a quantitative index of the distortion. Magnification is obtained if the viewing point is closer to the display that is the center of projection. Magnification, implies a compression of internal depth, with slanted surfaces becoming more frontal. We represent magnification and minification as the ratio of correct to actual viewing points. Thus, if one views from one-half the correct distance the magnification ratio is 2.0; if one views from twice the correct distance, the magnification ratio is 0.5. The changes in internal depth of objects in the virtual space corresponds to the reciprocal of the magnification ratio. Similar descriptions of virtual space can be generated for lateral displacements of the viewing point. Lateral displacements of the viewing point result in an additive combination of shear and magnification. The point to be stressed here is that these distortions are not due to any particular viewing point, but rather the relation between the actual and the correct viewing point.

Since we can define the real space, can calculate the virtual space, and can record judgments indicating perceived space, the psychological question becomes quite simple. When does the perception of space in graphic displays correspond to the geometrically specified space? Does compensation for distortion occur? Psychophysically, these become relatively easy questions to answer.

Before reviewing some of our results, let us consider how such a compensation mechanism might operate. As I asserted earlier, there is no optical information for distortion, and the nature or extent of any distortion is not given in the display. On what might a pictorial compensation be based? One alternative is that one recognizes the objects depicted, and the pattern match criteria are extremely broad. Thus one might recognize horizontal surfaces or right angles even if the geometry of the projection did not correspond to these spatial details. A second alternative is a much more active compensation process. What we have proposed, and what our results indicate is happening, is that the discrepancy between an actual viewing point and an assumed correct viewing point is evaluated, and is used to discount the effects of the geometric distortion caused by the dislocation of the viewing point.

I will review the results of a series of studies which support this proposal. This review is selected from several studies in which we have examined all possible distortions of displays of static objects and spatial layout, and their effects on perceived slant, depth, internal depth, height, width. In addition, we have explored the effects of geometric distortions of these dimensions of space on moving objects and layouts, and in all cases a single pattern of results emerges.

Distortions of Unfamiliar Objects

One set of studies have dealt with the effects of geometrical distortions on perceived depth of unfamiliar objects. Magnification or minification induced by viewing a display from too close or too far away (relative to the correct center of projection) causes a compression or expansion of virtual space. We asked people to make magnitude estimates of the internal depth of objects depicted on a CRT screen. The procedure that was used was to project concentric irregular five-sided shapes. The corresponding vertices of the shapes were connected by lines to increase linear perspective information. The overall impression was of looking into an irregularly shaped tunnel which receded into the distance. The participants were asked to judge the objects' internal depth. The objects were computer drawn, and displayed on a CRT screen which the observers viewed while in a chin rest to assure appropriate viewing distances. In the first experiment the viewing point for all conditions was constant at 112 cm. while the center of projection was varied to result in a range of distortions of virtual space equivalent to magnifications of 0.25 to 3.0.

If perception of the displayed space were determined by the projection, we should expect a correspondence between perceived space and the distortion virtual space specified by the display. In fact, as can be seen in Table 1, there was an extremely close correspondence between the actual judgments and those expected on the basis of the geometric distortion. In general, internal depth was accurately perceived when the CRT screen was viewed from the correct center of projection.

Table 1
Power Functions for Magnification
Viewing Distance Constant

Magnification	Coefficient	Exponent
0.25	4.67	0.58
0.50	1.86	0.69
1.00	1.32	0.72
2.00	0.60	0.73
3.00	0.61	0.70

A 4X minification resulted in an expansion of perceived space by a factor of approximately 4. Similarly, magnifications resulted in compressions of perceived space as expected from the induced distortions of geometric information.

It is clear from these results, that there is a close relationship between the perception of internal depth represented in graphic displays, and the nature of the geometric information provided by the display. Inducing distortions in the display projections results in regular and predictable errors in perception. If distortions are introduced by projecting the display to a point other than the normal viewing point, corresponding distortions in perception result. Appropriate choice of a center of projection in designing graphic displays is crucial for perceptual judgments, at least under certain circumstances.

It is to be expected that there would be a close relationship between judged depth and distortion. Since there is no optical information for distortion, judgments correspond to that specified by available information. The projective distortions of magnification and minification can be generated in two ways: moving the center of projection while maintaining a constant viewing position as was done above, and by moving the viewing point while maintaining a constant location for the center of projection. In this latter case, the degree of magnification (and of the expansion or contraction of perceived space) is perfectly related to viewing distance. Under such conditions, a non-optical basis for compensation exists, and individuals could, in principle, discount the effects of variation in viewing point.

To determine whether such discounting of distortion occurs within the context of the perception of unfamiliar objects, magnifications ranging from 0.33 to 4.0 were created by projecting the display to a point 112 cm away from the screen while the display was viewed from points between 28 cm and 337 cm away. Since magnifications are related to the ratio of actual to correct viewing distance, these viewing conditions result in projective distortions equivalent to those used in the preceding experiment. Equivalent distortions of perceived depth are expected in perception, *in this case, if only the projection affects judgment.*

Subjects' judgments however, showed no effect of the geometric distortions in this case. As shown in Table 2, in spite of a twelve-fold distortion

Table 2
Power Functions for Magnification
Viewing Distance Varied

Magnification	Coefficient	Exponent
0.33	1.02	0.77
0.50	1.12	0.74
1.00	1.09	0.76
2.00	1.04	0.78
4.00	1.17	0.72

of virtual space induced by the geometric distortion, there is no effect demonstrated in perceived depth; power function coefficients are constant. These data conclusively demonstrate that compensation for the distorting effects of magnification occurs when the distortions are caused by moving the viewing point, but not when equivalent distortions are caused by moving the center of projection. Since the distortions are discounted only when the distortions are correlated with viewing distance, we have suggested that a comparison between the actual distance and some assumed correct or standard distance froms the basis for compensation.

Effects of Familiarity

It is clear that individuals can actively discount the distorting effects of projective transformations of displayed objects. The commonly reported inability of individuals to notice such distortion seems to be due to some additional factor. Under some conditions people do not appear to notice that a distortion is present. We distinguish this from a more active compensation because some failure to discriminate or loss of sensitivity seems to occur.

Perceptual judgments of spatial layouts can involve two different activities. One is the registration and processing of projective geometric information. A second may simply involve a perceptual categorization of an object. If something is categorized as a cube, judgments of its relative dimensions may be influenced by assumptions concerning known qualities of the object.

To explore such an effect, further experiments were conducted that were analogous to the ones discussed above. A series of rectangular solids with equal length and width were created. The stimulus objects were subjected to two Euhler transforms so that the two sides were at a 45 degree angle to the screen, and the top was at 10 degrees relative to the screen. Such an arrangement gives good 3-point perspective. In one experiment, the subjects viewed the screen from a distance of 112 cm. while the objects were displayed with centers of projection ranging from 28 cm to 450 cm. These relations give magnifications which result in distortions of virtual space of from 0.25 to 4.0. The observation conditions were identical to those described in the first experiment above which resulted in large distortions of judgment.

In contrast, judgments of the internal depth of the regular parallelopipeds showed little effects of the distortion of virtual space. Although there are visible, significant effects of the effects of the distortion of virtual space, their size was an order of magnitude less than expected from the distortion. Thus is appears that the perceptual effects of an expansion of compression of virtual space is severely restricted when a familiar, regular target object is used.

In a further experiment using the rectangular solids, the displays were projected to a constant distance 112 cm from the screen, But the displays were viewed from various distances that resulted in expansion or contraction of virtual space by factors ranging from 0.25 to 4.0. In this study the degree of distortion was directly related to the distance from the subject to he display screen. The range of the effect of the geometric distortions is reduced relative to the preceding experiment, and statistically, the perceptual effects of distortions of virtual space are reduced when the degree of distortion is caused by moving the observer's viewing point. However, the absolute magnitude of this compensation is extremely small. The familiarity or regularity of the objects renders the perceptual system quite insensitive to projective distortions.

Insensitivity To Distortions

The results of the preceding experiments show that for regular objects, it is virtually impossible for observers to detect projective distortions of their virtual dimensions. The extent of this insensitivity is revealed by a series of signal detection experiments undertaken to assess the sensitivity to geometric distortion. The method used was a modified stair-case scaling procedure. The rectangular solid described above under 10 different degrees of distortion were projected on a CRT screen. Subjects were asked to simply indicate whether the depicted object appeared distorted (under various criteria). If the subject responded no, the experimental program increased the degree of projective distortion. If the subject responded yes they saw some distortion on two successive trials, the amount of distortion was decreased. This procedure effectively tracks the $d' = 0.707$ point. The intent was to compare different distortions that corresponded to a constant value of d'.

In three initial experiments, using different definitions of distortion, it was impossible to obtain any measure of d'. Magnifications resulting in a thirty-fold compression of virtual space were not reported as distorting the objects.

To simplify the task, the procedure was changed to a two-alternative forced choice paradigm, and only one object (a cube) was used in place of the series of rectangular solids. Pairs of cubes were presented successively. One was undistorted (i.e. was projected to the viewing point), the other was determined to the extent determined by the staircase procedure. Using this procedure is was possible to make a crude estimate of sensitivity. The average value of distortion which corresponded to a d' of 0.707 was magnification equal to 2.8 for compression of space, and magnification of 0.33 for expansion. Thus, virtual space had to be compressed or expanded by a factor of three in order for observers to discriminate a shape

distortion at this low level of sensitivity. In addition, there was a great deal of intra-subject variability. There appears to be no fixed separation of the underlying signal and noise distributions, rather sensitivity changes greatly from trial to trial. The processes that are involved in recognition of regular objects appear to greatly interfere with the ability to judge displayed space simply on the basis of projected information.

Extension to Motion-Carried Information

A second important source of information for space (in addition to static gradients) is provided by motion perspective, which we define as the dynamic changes in the optic array which occur as a result of relative motion between a surface and an observer (or in the mechanical case between a surface and a camera or other sensor).

Gibson showed that optical transformations provide information for spatial layout in one special case: translatory motion of an arbitrary surface; there exists one other special case for which the relationship between optical motions and spatial layout have been demonstrated: that for an arbitrary motion of a rigid, planar surface. We assert without here providing a proof that it is impossible to relate optical motion to spatial layout for any arbitrary motion of any arbitrary object.

The existence of the second special case of optical motions specifying spatial layout was foreseen by Gibson and Gibson (1957) who argued that any continuous *sequence of perspective transformations* provided sufficient information for the perception of rigid motion. While this suggestion is not entirely correct, it provided an initial impetus for subsequent analyses of motion-carried information.

In the following discussion we will describe the information for spatial layout that is provided by array motion, and discuss the distortions of this information that occur when graphic displays of moving objects are viewed from the incorrect point. There are two possible ways to describe such information. We can consider this information as contained in a "continuous sequence of perspective transformations". Thus the visual system might register *texture gradients* and their differentials. Or we can use an alternative characterization of dynamic spatial information as involving "velocity fields", "flow gradients", or "motion perspective". This alternate would suggest that *velocity relations* among points in the visual field would be registered by the virtual system.

Under normal conditions (directly viewing the world, or viewing a graphic display from the correct location) these two approaches yield identical solutions for spatial layout. Distances, sizes, shapes, and orientations computed from a transformation sequence are identical to those computed from velocity fields. In fact, Gibson and his colleagues often seem to refer to these two approaches as if they involve synonymous concepts.

However, if we consider the distortions induced in spatial information by dislocations of the viewing point of graphic displays, then the two approaches are no longer equivalent. In fact, under some conditions they yield diametrically opposed predictions, e.g., transformation sequences predicting an expanded space and velocity fields predicting a compressed space, *under the same conditions*. Because of the enormous theoretical and practical importance of such distortions of graphic displays of space, both the transformation sequence and velocity field approaches will be developed.

Since any displacement of a rigid object can be broken into a translational and a rotational component, we will begin by simply considering translation. Let us take the case of a single frontal-parallel square centered on the line of sight in an oculocentric coordinate system, (the object is centered on the Z-axis). With pure translation along the X-axis, there occurs a series of perspective transforms which cause increased foreshortening and perspective convergence of the square's sides *in the projection*. These transforms are unique to a square and are proportional to the ratio of the displacement to the distance between the eye and the frontal surface.

From the standpoint of motion perspective, the motion of the square sets up a velocity field, such that the velocity of any point in the array is proportional to its distance and azimuth in the array. Again, this pattern of velocities is unique to this specific motion of a rigid square.

A similar set of descriptions can be provided for pure rotation. Let us consider a unit square rotating about a vertical axis. At t_0 it is frontal and the object is projectively a square. At t_1, the object has rotated through W, and undergone a perspective change and a foreshortening. The ratio of the angular width to angular height at any instant is equal to the cosine of the angle (θ) of the surface with respect to the line of sight. If the velocity of rotation is constant, f (θ) over time will be linear. If it is not linear, the perspective sequence specifies a change in velocity. If it is not monotonic the perspective sequence specifies an oscillation or reversal of motion, since direction of motion is specified by the shape of this function. Thus the sequence of perspective transforms specifies, direction of motion, orientation, changes in velocity, constant shape of the object, and ratio of width to internal depth of the object. Since the width and internal depth are equal, any off-axis point (e.g., a corner) describes a circular path in space.

Consideration of the information provided by the velocity flow field yields an identical spatial layout based on different optical relationships. As the square rotates, a motion perspective gradient is set up by the array movement of each point on the square. The velocity of the far edge will be smaller in absolute magnitude, and opposite in sign compared to the velocity of the near edge. This velocity difference is proportional to the internal depth separation of the edges and consequently specifies the orientation of the surface. The velocity differences are greatest at $\theta = 0°$ and at this point specify internal depth. The velocities themselves specify direction of rotation simply because the direction of the greater velocity vector is the direction in which the front edge moves. The motion perspective pattern generated by the horizontal and vertical sides is unique to a rigid square and thus specifies constant shape of the surface, and a circular path of rotation.

The relationships summarized above describe the potential information provided by motion-carried information conceived of as a sequence of perspective transformations or as a gradient of array velocities. If the display is not viewed from the correct center of projection, the information contained in the pictorial array is distorted, i.e., it corresponds to a transformed virtual space. These distortions will be discussed below.

For the translational component of motion-carried information, the distortions of virtual space are easy to describe, and are identical for the analyses based on the transformation sequence, and for one based on velocity gradients. In the case of simple translation, distortions of information are equivalent to those which occur with static displays.

For the rotational component of motion carried-information we do not know the effects of geometric distortions on perception. In addition, we can not even be sure, at a theoretical level, of what effects to expect based on geometric distortion. Although the sequence-of-transformations definition and the velocity-gradient definition of motion-carried information are congruent, and lead to identical descriptions of virtual space with normal viewing, they are in conflict under conditions of optical distortion. We will describe this conflict by first considering the effects of magnification as predicted by both approaches.

Let us consider a unit square which is initially parallel to the frontal, and which rotates smoothly about a vertical axis bisecting its sides. We adopt an oculocentric coordinate system with the coordinates normalized to make the distance from the center of projection to the display equal to 1 (this is the same system used in Farber and Rosinski (1978), Rosinski and Farber (1979) and in previous reports). At any instant the virtual orientation of the square θ' is given by $\tan \theta = \tan\theta$, thus for any $m =! 1.0$, the virtual orientation will be nonlinearly related to θ. For equal changes in θ, unequal changes in θ' will occur.

Likewise, at any instant, magnification compresses internal depth. Any point in virtual space, $P(x,y,z)$, is transformed into $P(x,y,z/m)$ under a magnification of m. These effects are also a function of θ, the surface orientation. Thus when the square is parallel to the frontal, its vertical and horizontal sides both equal 1.0. When the square has rotated to 90° from the frontal, with $m = 2.0$, its internal depth (horizontal) will be compressed to 0.5 units, while the verticals will remain at 1.0 units in size in the virtual space. Since the virtual size of the square's *horizontal* elements (depth) will oscillate between 1.0 (and 0.5) the square will be defined as elastic or non-rigid. Under rotation, a selected off-axis point (say a corner), will describe an elliptical path of motion with the ratio of the major and minor axes of the ellipse equal to the magnification ratio.

To summarize, if we describe the virtual space under magnification as a sequence of projective transforms we expect:

1. Verticals in front and behind are the same size.
2. Horizontals are compressed with $m > 1.0$ and expanded with $m > 1.0$.
3. The oscillation in size specifies non-rigidity or 'rubbery distortions.
4. The path of motion of an off-axis point is an ellipse with major axis parallel to the frontal for $m > 1.0$ or with major axis perpendicular to the frontal for $m > 1.0$. The magnification ratios define the ratios of major to minor axis.

Farber (1972) has shown that the virtual space specified under rotation is transformed in different ways if we consider velocity gradients. To briefly outline such an analysis let us consider the same square ABCD, were $A = (X_1,Y_1)$ $B = (X_2,Y_2)$, $C = (X_2, -Y_2)$ and $D = (X_1, -Y_1)$, with $X_2 = -X_1$ and $X_1 > 0$. As the square rotates under magnification let us consider a description of virtual space *as specified* by the velocity field. Consider the two vertical sides of the square $AD = V_1$ and $BC = V_2$. Be definition $V_1 = V_2$, and $V_1/V_2 = 1.0$. In the transformed virtual space

$$\frac{V_1'}{V_2'} = \frac{1 - K \sin\theta\, X_1}{1 + K \sin\theta\, X_1}$$

where $k = (1-m^{2)}$. Since $X_2 = X_1$

$$\frac{V_1'}{V_2'} = \frac{1 - K \sin\theta\, X_1}{1 + K \sin\theta\, X_1}$$

Since the ratio of verticals is a function of θ the orientation, the square changes its *vertical* extent with rotation and therefore must be elastic. In particular, for a frontal surface, the two verticals are equal in size. As the square rotates, the virtual size of the rear vertical is greater than the front for $m > 1.0$. The virtual size of the front vertical is greater for $m < 1.0$.

If the square were lying flat, perpendicular to the frontal, with a vertical axis (or if we were considering the horizontals of a unit cube) the identical analysis of the virtual size of horizontal elements can be made. With $m > 1.0$ rear horizontals are larger compared with the front horizontals, for $m < 1.0$ the front is larger. (As before rear means behind the axis.) Under such circumstances, distortion of internal depth depends on position as well as magnification. For $m > 1.0$ horizontal extents behind the axis are extended, extents in front of the axis are compressed. The reverse holds for $m < 1.0$.

Let us combine these two changes by considering the distortions of a rotating cube under magnification. Since the rear verticals and horizontals are greater than the front ones, the rear surface will be larger. The vertical object will then be trapezoidal solid or a truncated pyramid. Select any one vertical side. On the near side it will be a small square, as it rotates it becomes a trapezoid, and then a large square at the far side, etc. Thus any surface will elastically distort in

both size and shape.

If we select an off-axis point, its path of motion will describe an ovoid. Farber (1972) gives its actual locus as follows. We select point $(X_1,0)$ and the corresponding virtual point $(X_1',0)$ in virtual space. As θ varies, $X_1'(\theta)$ is given by

$$X_1'(\theta) = \frac{[mX_1(\cos^2\theta + m^2\sin^2\theta)^{1/2}]}{[1 + (1-m^2)\sin\theta\, X_1]}$$

As Farber points out this is a rather complicated point position determined by the magnification ratio, the degree of rotation of the real surface, and the location of the original point in space. In general, however, for magnification ($m > 1.0$) the path will be deeper than it is wide, and of minification ($m < 1.0$) it will be wider than it is deep.

Although the perspective transform (PT) and the velocity gradient (VG) definition of motion-carried information for space are equivalent under normal viewing, they are not under optical distortion. The major differences are as follows for magnification of a unit cube:

a. The virtual object has front and rear faces of equal size under PT, but has a larger rear face under VG.

b. The axis of rotation is centered under PT, but is closer to the front face under VG.

c. Internal depth is compressed under PT, but expanded under VG.

d. Under PT, a frontal square elastically distorts into a rectangle with rotation. Under VG the square elastically distorts into a trapezoid.

Thus, it appears that depending on whether the virtual system actually registers PT and VG, we should expect radically different layouts of perceived space. The situation is further complicated by the fact that PT and VG accounts are consonant for translational motion, even under distortion. If the visual system were to register only VG, the translational and rotational components of any compound motion would be in conflict.

A series of studies were performed to evaluate various theoretical expectations. In the first series of experiments, subjects were asked to judge the slant of a surface depicted at nine different physical slants, much as in earlier work in this project. In one experiment the display was viewed from a constant viewing position while the center of projection was varied across conditions to result in five levels of magnification. In a second, viewing position was varied, resulting in a comparable set of five magnifications which, in this case, were correlated with viewing distance. In a third experiment, projection conditions were equivalent to the third experiment, but the display was viewed through a lens to eliminate oculo-motor cues to the screen location. In each of these experiments, surface orientation was specified by both texture gradients as well as motion-carried information carried by the lateral translation of the objects. In each of these experiments, the results were closely comparable with our previous orientation studies. With moving as well as with static stimuli, perception was affected by distortion when no relationship between distortion and viewing situation was apparent. When the degree of distortion was correlated with viewing distance, compensation for distortion was observed. However, elimination of ocular-motor cues did not substantially increase perceptual distortion, indicating that if oculo-motorically given viewing distance is important in compensation, it does not affect the magnitude of the original distortion.

A set of studies similar to those above were performed with moving objects with results comparable to those obtained earlier with static objects.

These six studies show that translational motion carried information has the same effects as static textural information both under normal and under two types of distorted viewing conditions.

Of especial interest is a further set of four studies that evaluated the effects of rotational motion under distorting viewing conditions. Viewing conditions were as described above, except that several different dimensional judgments were sought. The results showed that the effects of the geometric distortions on perception were greatly minimized by the presence of regular/familiar target objects. Thus even with motion carried information, geometric distortions that conflict with assumptions underlying target regularity are discounted. The effects of distortion remaining indicated that the basis for the pick-up of motion carried information was the registration of the sequence of linear transforms, not the velocity gradients. Thus it appears that identical perceptual processes underly both the perception of static and dynamic displays.

Implications

The theoretical conclusions to be drawn from this work seem to be clear-cut. With irregular or unfamiliar targets, and novel visual display systems, the geometric projection is the major, if not sole, determiner of space perception based on graphic displays. For display applications intended for unusual environments, work must concentrate on increasing display fidelity. Discovery of basic processes in perception, especially in terms of the integration of several different sources of visual information (eg. binocular, monocular, motion-carried) is critical. In addition, I would like to see the growth of exploratory studies. We need to relate the kinds of results that I have reported to actual control activities. A pressing question concerns the relationship between perception based on graphic displays, and remote piloting and video maneuvering.

With familiar display systems, our results suggest that geometric distortions can be discounted by the perceptual system. The discrepancy between the actual viewing point for a display and some assumed correct viewing point is used to eliminate the effects of distortion in space perception. An obvious, but important question concerns the nature and amount of experience that maximizes this effect. How can we train display operators and users to make them maintain perceptual accuracy in spite of geometric distortions?

For regular, familiar target objects, the categorization of these objects may reduce or eliminate sensitivity to spatial information. This raises important questions. What is the interaction between training and sophistication, and the ability to accurately use spatial information? Can we, for certain applications, degrade the fidelity of a display effectively. If details of spatial information are unimportant in some instances, can we save display and computing costs by using symbols rather than accurate graphic representations. In a related vein, if sensitivity to distortion is low in some cases, can we more effectively use bandwidth by updating displays only when the displays are *perceptually* different. This is especially important in light of the finding that static and dynamic displays are both processed in terms of liner perspective transformations.

Future challenges lie in exploratory developments making use of, and further driving additional basic research.

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Hawaii Laboratory
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Kailua, HI 96734

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Scientific Advisor
Commandant of the Marine Corps
Code Rd-1
Washington, D.C. 20380

HQS, U.S. Marine Corps
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Washington, D.C. 20380

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Agency
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Arlington, VA 22209

Dr. Judith Daly
System Sciences Office
Defense Advanced Research Projects
Agency
1400 Wilson Blvd.
Arlington, VA 22209

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ACT 200
Atlantic City Airport, NJ 08405

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Blacksburg, VA 24061

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Washington, DC 20418

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Perceptronics, Inc.
6271 Variel Avenue
Woodland Hills, CA 91364

Dr. Robert Williges
Human Factors Laboratory
Virginia Polytechnic Institute and State University
130 Whittemore Hall
Blacksburg, VA 24061

Dr. Meredith P. Crawford
American Psychological Association
Office of Educational Affairs
1200 17th Street, NW.
Washington, D.C. 20036

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Department of Psychology
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Nashville, Tennessee

Dr. Christopher Wickens
University of Illinois
Department of Psychology
Urbana, IL 61801

OTHER ORGANIZATIONS

Dr. Edward R. Jones
Chief, Human Factors Engineering
McDonnell-Douglas Astronautics Company
St. Louis Division
Box 516
St. Louis, MO 63166

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Department of Industrial Engineering
North Carolina A&T State University
Greensboro, NC 27411

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Bolt Beranek & Newman, Inc.
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New Mexico State University
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